A Comparative Study of Differential and Noncoherent Direct Sequence Spread Spectrum over Underwater Acoustic Channels with Multiuser Interference

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Abstract—Spread spectrum communication provides a robust solution for underwater acoustic communication over noisy or otherwise unfavorable channels while allowing multiple users to occupy the same bandwidth at the same time. In this study we compare two variants, differential and noncoherent, of direct sequence code division multiple access (DS-CDMA) side-by-side on their performance over a range of channel conditions. Analysis of experimental data collected from the UNET06 experiment in St. Margarets Bay, Nova Scotia, Canada, reveals a tradeoff in performance between these two methods when the interference level and data rates change. Through further simulations we develop a good picture of the range of channel conditions for which one method will outperform the other. These results depend largely on the channel coherence value and the interference level: specifically, the differential scheme is better suited to coherent channels with low interference levels while the noncoherent scheme achieves better performance in high-interference scenarios and as the channel coherence decreases. Further, we observe that the noncoherent scheme is more robust relative to the differential alternative when the rate increases from 1 bit to 2 bits per symbol transmission.

I. INTRODUCTION

Bandwidth is an invaluable resource in the UWA channel due to the considerably narrow (compared to radio) range of frequencies available. In applications with multiple users, such as autonomous underwater vehicle (AUV) networks and underwater sensor networks (UWSNs), a considerable effort must be devoted to managing the time-frequency grid in order to avoid collisions (overlap in time and frequency) between different messages. Any technology that allows loosening of restrictions on time and frequency stands to improve data rates and energy consumption properties of the system in which it is deployed. Direct-sequence code-division-multiple-access (DS-CDMA) has generated a great deal of consideration for multiuser applications over the past decade; see e.g., [1]–[4] and references therein. Through the use of a spreading gain and mutually orthogonal user sequences, a certain amount of time-frequency overlap becomes tolerable.

In this paper, we compare two variants, namely differential and noncoherent DS-CDMA, side by side on their performance over a range of channel conditions. Differential receivers for spread spectrum transmissions have been used in e.g., [4], [5], while noncoherent receivers have been used in e.g., [6]. These methods have low receiver complexity relative to adaptive coherent receivers such as [3], [7].

This study begins with an examination of real data taken from St. Margarets Bay, Nova Scotia, Canada in 2006 where we add interference and noise to evaluate each demodulation method side-by-side. When the interference level and data rates change, there exists a tradeoff in performance between these two methods. We are thus motivated to pursue a thorough simulation study to determine which scheme is better suited to which channel conditions. Our simulations are split into four cases, each of which is defined by the presence (or lack thereof) of two factors: multiuser interference and channel coherence loss. Specifically, these four scenarios are:

1) perfect channel coherence and no multi-user interference
2) perfect channel coherence and with multi-user interference
3) channel coherence loss and no multi-user interference
4) channel coherence loss and with multi-user interference

Both 2-ary (one bit per transmitted symbol) and 4-ary (two bits per symbol) transmissions were included for all simulated and experimental results.

In experimental and simulation studies, we observe that the differential scheme is better suited to coherent channels with low interference levels while the noncoherent scheme achieves better performance in high-interference scenarios and as the channel coherence decreases. Further, the noncoherent scheme is more robust relative to the differential alternative when the rate increases from 1 bit-per-symbol to 2 bits-per-symbol. The study in this paper could be useful in deciding which scheme to use in a particular application environment where channel coherence and the interference level can be evaluated or predicted.

The rest of this paper is organized as follows. System model is presented in Section II and experimental study is presented in Section III. Section IV contains simulation results and Section V contains concluding remarks.

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II. System Descriptions

We first describe a multiuser system based on conventional direct sequence spread spectrum (DSSS). A user u is assigned a pseudo-noise (PN) sequence of length N_c, defined as $c[n] \in \{\pm 1\}, n = 0, 1, ..., N_c - 1$. The transmitted chip sequence from user u is

$$x_u[n] = \sum_i s_u[i]c[n - iN_c], \qquad (1)$$

where n is the chip index, i is the symbol index, and $s_u[i]$ is the information-bearing symbol.

Let $h[n, l]$ denote the time-varying channel at the baseband, where n is the time index and l is the lag index. The received signal in the presence of asynchronous multiuser transmissions is

$$r[n] = \sum_u \sqrt{P_u} \sum_l x_u[n - \tau_u - l]h_u[n - \tau_u, l] + w[n], \quad (2)$$

where P_u is the transmitted power, τ_u is the random delay for user u, and $w[n]$ is the additive noise.

A. Differential DSSS

A differential system encodes information relative to the previous symbols rather than to an arbitrary fixed reference in the signal phase [4], [5]. This is achieved by mapping the symbol information to a phase rotation that multiplies the usercode as

$$s_u[i] = e^{j\phi_u[i]}s_u[i - 1] \qquad (3)$$

where $\phi_u[i] \in \{0, \frac{2\pi}{M}, \ldots, \frac{2\pi(M-1)}{M}\}$ for differential M-PSK. The receiver, in turn, bases its symbol decisions on the phase differences between consecutive symbols.

In order to despread, the receiver employs a matched filtering operation between its own copy of $c[n]$ and the received signal $r[n]$, defined as

$$y_u[n] = \sum_{i=1}^{N_c} c[i]r[n + \tau_u + i]. \qquad (4)$$

The output $y_u[n]$ can be divided into three components: the intended transmitter's signal, the interference term, and the noise term. Matched filtering with the first term, the intended transmitter's signal, will yield, with abuse of language, a channel estimate, $\hat{h}[n, l]$, multiplied by the symbol phase rotation [5]. Note that the usefulness of this $\hat{h}[n, l]$ term as a channel estimate decreases as the channel becomes more rapidly time varying.

This technique can be quite useful for channels with a delay spread, since it allows consolidation of energy from all arrival paths. Assume that the channel has L taps in discrete time. The receiver forms the decision statistic, which is a vector inner product between y_u for the i-th and $(i - 1)$-th symbol durations [5], as

$$z_u[i] = \sum_{l=0}^{L} y_u[iN_c + l] \cdot y_u^*[(i - 1)N_c + l], \qquad (5)$$

where $*$ denotes complex conjugate. The symbol estimate $\hat{\phi}_u[i]$ is made according to

$$\hat{\phi}_u[i] = \operatorname*{arg\,min}_{\phi \in \{\frac{2\pi m}{M}\}_{m=0}^{M-1}} |\angle z_u[i] - \phi|. \qquad (6)$$

Note that in the case of perfect channel coherence (and neglecting noise and interference terms) one would have

$$z_u[i] = e^{\phi_u[i]} P_u N_c^2 \sum_{l=0}^{L-1} |h_u[iN_c, l]|^2, \qquad (7)$$

which maximizes the energy from all arrival paths. If the two consecutive channel realizations are dissimilar, however, then the term multiplying $e^{\phi_u[i]}$ in (7) will decrease and the effective SNR will suffer.

B. Noncoherent DSSS

We now define an alternative system that does not employ time domain reference signals, which should help reduce the effects of channel coherence loss compared to the previous system. This noncoherent system is one in which each user is assigned a group of mutually orthogonal usercodes (defined by c_{g_u}, where g_u has M choices). They are (nearly) orthogonal to each other and to all codes belonging to other users. The code index at time i, denoted as $g_u[i]$, depends on the information bits to be transmitted at time i. The number of codes assigned to each user is determined by the bits per symbol, 2^M. For user u, a transmitted chip sequence will appear as

$$x_u[n] = \sum_i c_{g_u[i]}[n - iN_c]. \qquad (8)$$

The receiver then despreads as in (4), but with each of its M usercodes, producing $[y_{u,0}[n], ..., y_{u,M-1}[n]]$. In order to determine which usercode was transmitted at each symbol interval, it determines which despreading result has the most energy. For example, the i-th symbol decision is

$$\hat{g}_u[i] = \operatorname*{arg\,max}_g \left\{ \sum_{n=iN_c}^{iN_c+L-1} |y_{u,g}[n]|^2 \right\}. \qquad (9)$$

The most important trait of this receiver is that it doesn't rely on reference signals, which reduces the effects of channel coherence loss as a source of error.

III. Field Testing

We now examine the data gathered at the UNET06 experiment at Saint Margarets Bay, Nova Scotia, Canada, in May 2006. Using real transmissions from six users, a multiuser system is simulated by superimposing all transmissions with randomized time offsets.

The signal bandwidth was 4 kHz, which leads to a chip duration of 0.25 milliseconds. The center frequency was $f_c = 17$ kHz. The spreading sequence length was chosen as $N_c = 511$, yielding a symbol duration of 127.75 ms. Data was transmitted through a 60 m deep channel over a range of 3.1 km. A channel impulse response is shown in Fig. 1.
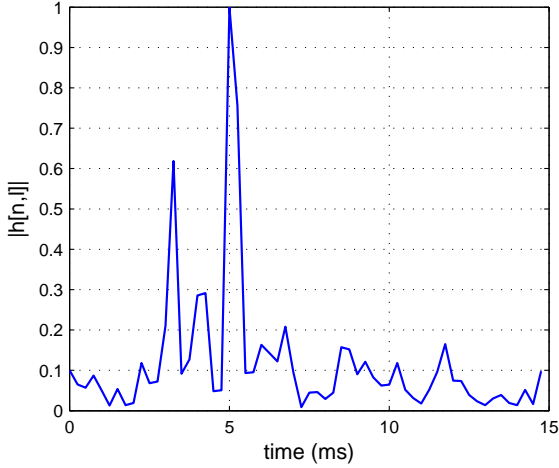
Fig. 1. One sample channel impulse response from experimental data, where multiple dominant paths are observable.

Fig. 2. BER results for experimental data. Solid lines: SIR = 10dB, dotted lines: SIR = 0dB, no line: SIR=−5dB

A. Noise and Interference

We begin by defining the noise and interference quantities to be included in our analysis. SNR defines the ratio of the energy of user u's signal at the receiver in baseband (denoted as P_u) to the corresponding noise energy. Under the assumption of additive white Gaussian external noise (AWGN), we have

$$\text{SNR}_u = \frac{P_u}{\sigma^2}, \qquad (10)$$

where noise samples are distributed with zero mean and variance σ^2. In our analysis we generate noise according to this distribution in order to vary the SNR.

For user u, the remaining users are considered to be interferers. The SIR defines the ratio of P_u to the energy of the superposition of the interfering signals (which may have different individual energies) in baseband at the receiver; i.e.,

$$\text{SIR}_u = \frac{P_u}{\sum_{u',u'\neq u} P_{u'}}. \qquad (11)$$

B. Field Test Results

Fig. 2 depicts the performance curves from the experimental data. An important observation for the 2-ary case is the effect of interference on both methods: decreasing the SIR below some value between 0 and −5 dB causes noncoherent demodulation to begin to outperform differential. In fact, it is quite significant that at SIR= −5 dB, differential's error floor is right at about 10^{-1}, which is an uncoded BER that most channel coding schemes cannot overcome. On the other hand, noncoherent's error floor levels off around 10^{-2}, which means it could be possible to achieve error-free transmission with the right channel coding at this SIR value.

In the 4-ary case we observe that the noncoherent method outperforms the differential one for the entire range of SIR values. We assume that this gap in performance is mostly due to the channel coherence value, especially since the performance of differential doesn't change much due to the SIR value, and since there is a high error floor for the almost
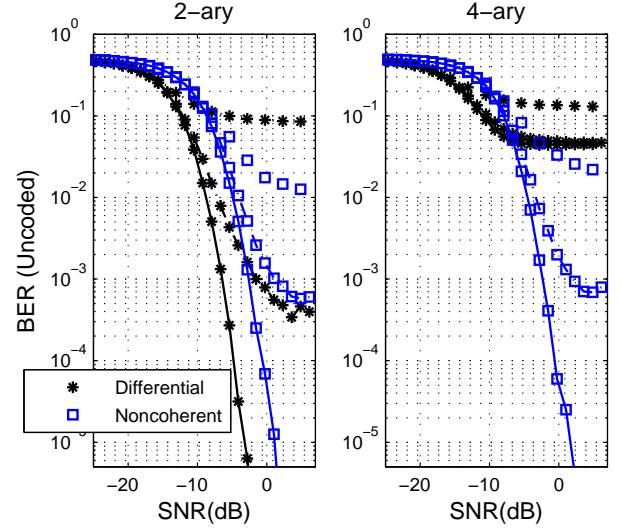
interference-free case (SIR = 10dB). This presents a strong argument in favor of the noncoherent method.

IV. SIMULATION RESULTS

Our simulation results wish to further explore the range of conditions for which one system will outperform the other.

A. Channel Model

The channel model used in simulation preserved some of the following key traits of the UWA channel:

- Multipath spreading (in our case the maximum delay is on the order of tens of milliseconds)
- Fast fading: the channel coherence time is less than one symbol duration.

Our channel model for the uth user, $h_u[n,l]$, is a collection of impulses with random complex valued path gains. The chip level channel coherence coefficient, defined by $\rho \in [0,1]$, is used to relate $h_u[n,l]$ with itself at another time such that

$$h_u[n,l] = \rho h_u[n-1,l] + v_u[n,l], \forall l \qquad (12)$$

where $v_u[n,l]$ is noise, independent of h, that exists to conserve energy between the two channel realizations. Channel taps are independent and identically distributed in simulations for simplicity.

To gain some insights, we can relate channel coherence to Doppler shifting caused by source/receiver and/or surface motion by using the Jakes' model [8]. Assuming a Jakes' model with τ fixed at the chip duration (in our experimental case, $\tau = 0.25$ms), the correlation coefficient ρ is related to the path velocity v as:

$$\rho(v) = J_0 \left(2\pi f_c \frac{v}{c} \tau \right) \qquad (13)$$

where c is the propagation speed and J_0 is a zero-order Bessel function of the first kind. The relationship in (13) is displayed
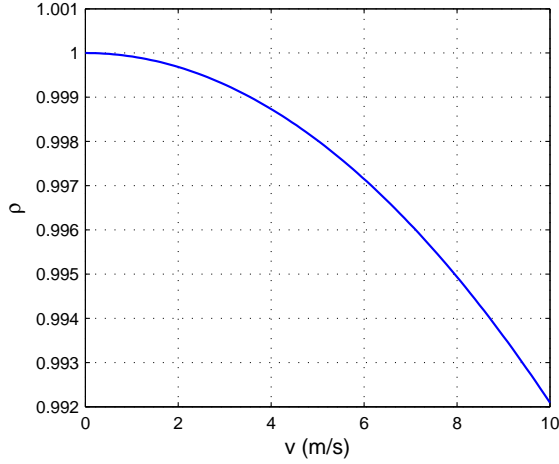
Fig. 3. Relationship between path velocity v and ρ as in equation (13): $c = 1500$m/s, $f_c = 17$kHz, $\tau = 0.25$ms
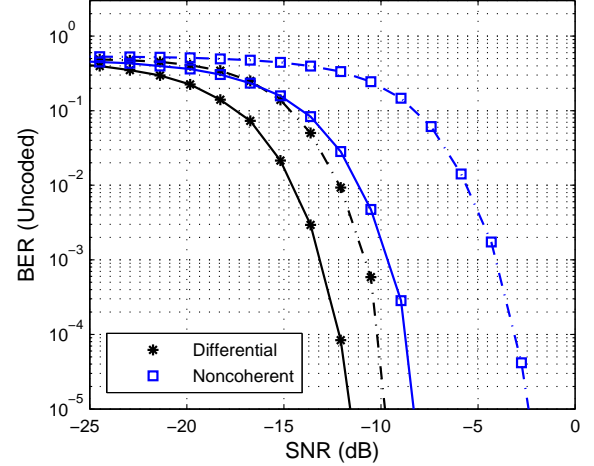

Fig. 4. BER results for simulation with no interference and perfect channel coherence. Solid lines: 2-ary transmission, dotted lines: 4-ary

in Fig. 3.

Our simulated channel exists for 80 chip durations, while we use $N_c = 511$ for the spreading sequence length. Other parameters are the same as in experimental studies.

B. Case 1: perfect coherence and no multiuser interference

We first analyze the performance of each system with $\rho = 1$ and no interference. Fig. 4 shows that differential enjoys about a 3dB performance increase over noncoherent in the 2-ary case and even more of an improvement in the 4-ary case.

C. Case 2: perfect coherence and with multiuser interference

We now add multiuser interference while keeping $\rho = 1$ to look for a tradeoff in performance due to SIR. As shown in Fig. 5, there exists an interference level for which noncoherent begins to outperform differential for the 2-ary case. The difference in error floor values at SIR$= -10$dB points to noncoherent being a better choice than differential for high interference cases. On the other hand, in the 4-ary case, we observe no clear choice when SIR$= -10$dB and we can assume that differential is a better choice for higher SIR values than -10dB.

D. Case 3: coherence loss and no multiuser interference

We now identify the effects of channel coherence on each system's performance without multiuser interference. We expect that changing only the channel coherence value will also yield a point where the noncoherent system begins to outperform the differential one. We decrease ρ and observe the BER performance of each system in a single-user scenario. By examining Fig. 6 we can find what we call the ρ crossing point: the value for which both systems have similar performance. We select $\rho = 0.9986$ which, in the case of our experimental parameters, corresponds to a path velocity of about 4.2 m/s. When ρ is smaller than the critical value, noncoherent outperforms differential, and vice versa.
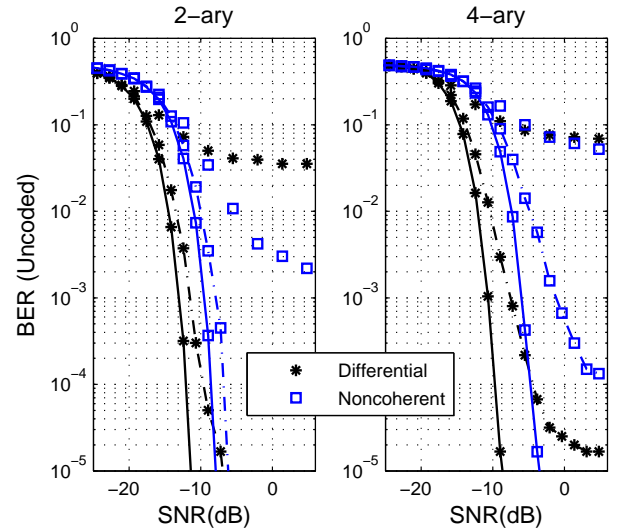
Fig. 5. BER results for case 2: perfect channel coherence with multi-user interference. Solid lines: SIR = 10dB, dotted lines: SIR = 0dB, no line: SIR = -10dB

E. Case 4: coherence loss and with multiuser interference

For the final simulation case, we fix ρ at its crossing point (i.e., $\rho = 0.9986$ from Case 3) and examine the BER performance to see how changing the interference level favors one system over the other. By examining Fig. 7, we observe a widening gap in performance between differential and noncoherent as the SIR becomes more negative. That lower SIR values favor noncoherent is consistent with our findings from Case 2. It is interesting (in that case and this one) to observe how robust the noncoherent system is compared to the differential one in the presence of interference. In this case in particular, when SIR reaches -10dB, differential is virtually useless for both rates while noncoherent 2-ary still performs capably. Even noncoherent 4-ary could still be useful depending on the application and the channel coding used.
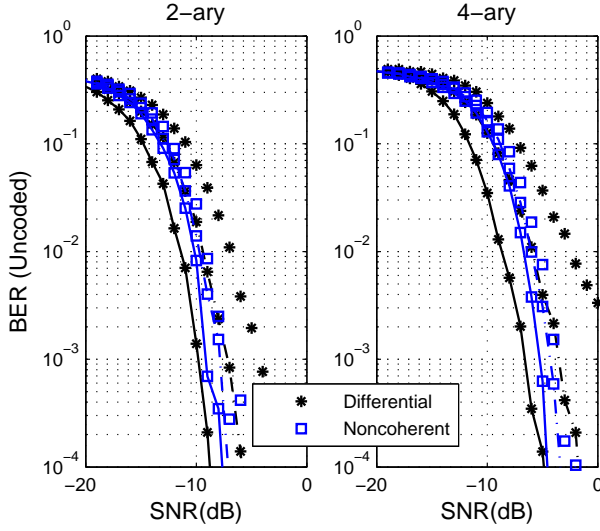
Fig. 6. BER results in the presence of no interference but with channel coherence loss. Solid line: $\rho = 0.9988$, dotted line: $\rho = 0.9980$, no line: $\rho = 0.9972$

Fig. 7. Simulated BER results with $\rho = 0.9986$ and multi-user interference. Solid lines: SIR = 10dB, dotted lines: SIR = 0dB, no line: SIR = −10dB

V. CONCLUSION

We presented a side-by-side comparison of differential and noncoherent DS-CDMA over UWA channels. By using experimental and simulated data and changing the interference and channel coherence levels, we determined when one method would outperform the other, in terms of BER performance. Specifically, our observations are as follows:

- The differential scheme is favorable when the channel coherence is high and the multiuser interference is light.
- The noncoherent scheme is favorable when the channel coherence is low or when the multiuser interference is severe.
- Noncoherent is a more robust choice when increasing the modulation alphabet from 2-ary to 4-ary.

The study of this paper can be used to facilitate the choice between differential and noncoherent schemes for a particular application scenario where the channel coherence and interference level can be measured or predicted.
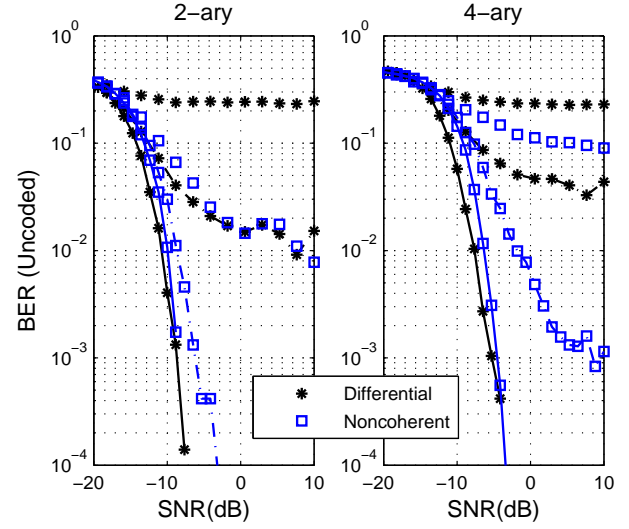
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